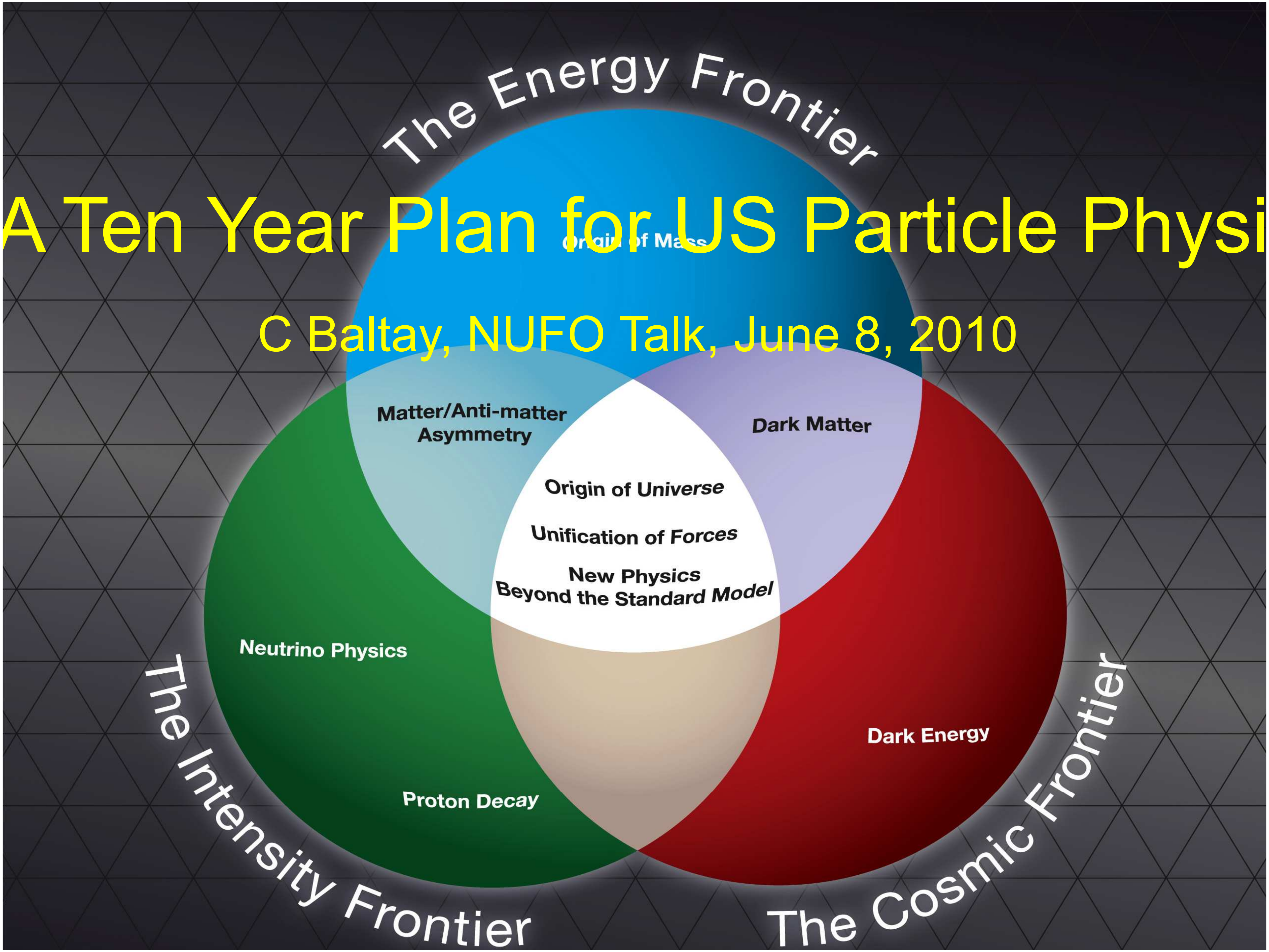
A Ten Year Plan for US Particle Physi

C Baltay, NUFO Talk, June 8, 2010



US Particle Physics: Scientific Opportunities

A Strategic Plan for the Next Ten Years

Report of the
Particle Physics Project Prioritization Panel

May 29, 2008

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Report Translated into English by Judy Jackson

Fundamental Questions in Particle Physics

- What are the basic constituents that the Universe is made of?
  - Quarks and Leptons, Dark Matter, Dark Energy, ???
- What are the forces enabling these constituents to form all that we see about us?
  - Gravity, Electromagnetic, Nuclear Forces, ???
- What are the laws of Nature that govern these and drove the evolution of the universe to its current state?
  - Newtonian Mechanics, Quantum Mechanics, Relativity, String Theory???

The Standard Model of Particle Physics

The Fundamental Constituents

Six Quarks d s b

u c t

Six Leptons e μ τ

ν_e ν_μ ν_τ

The Basic Forces

Gravity----from Newton to General Relativity

graviton g

Electroweak---Unification of electromagn and weak nucle

γ , W, Z

Strong Nuclear---Quantum Chromodynamics

gluon g

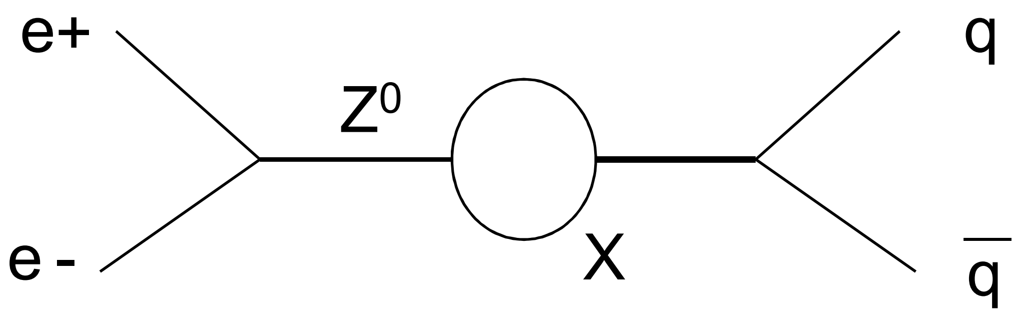
The Excitement in Particle Physics

- Particle Physics has been very successful in creating a major synthesis, the Standard Model, that explains to a high accuracy almost all experimental observations so far
- However recent results show that there is new physics Beyond the Standard Model
  - Tevatron, LEP, SLD experiments strongly point to new physics at the Terascale
  - Neutrino Oscillations: Neutrinos have mass, neutrino mixing
  - Missing Mass in the Universe: Dark Matter
  - An accelerating Universe: Dark Energy
  - No Quantum Theory of Gravity—TOE, GUT, String Theory???

These discoveries make Particle Physics richer and more exciting then ever before. Over the past decade the field has developed new cutting edge instruments to address these new physics questions. We expect fundamental new discoveries in the coming decade.

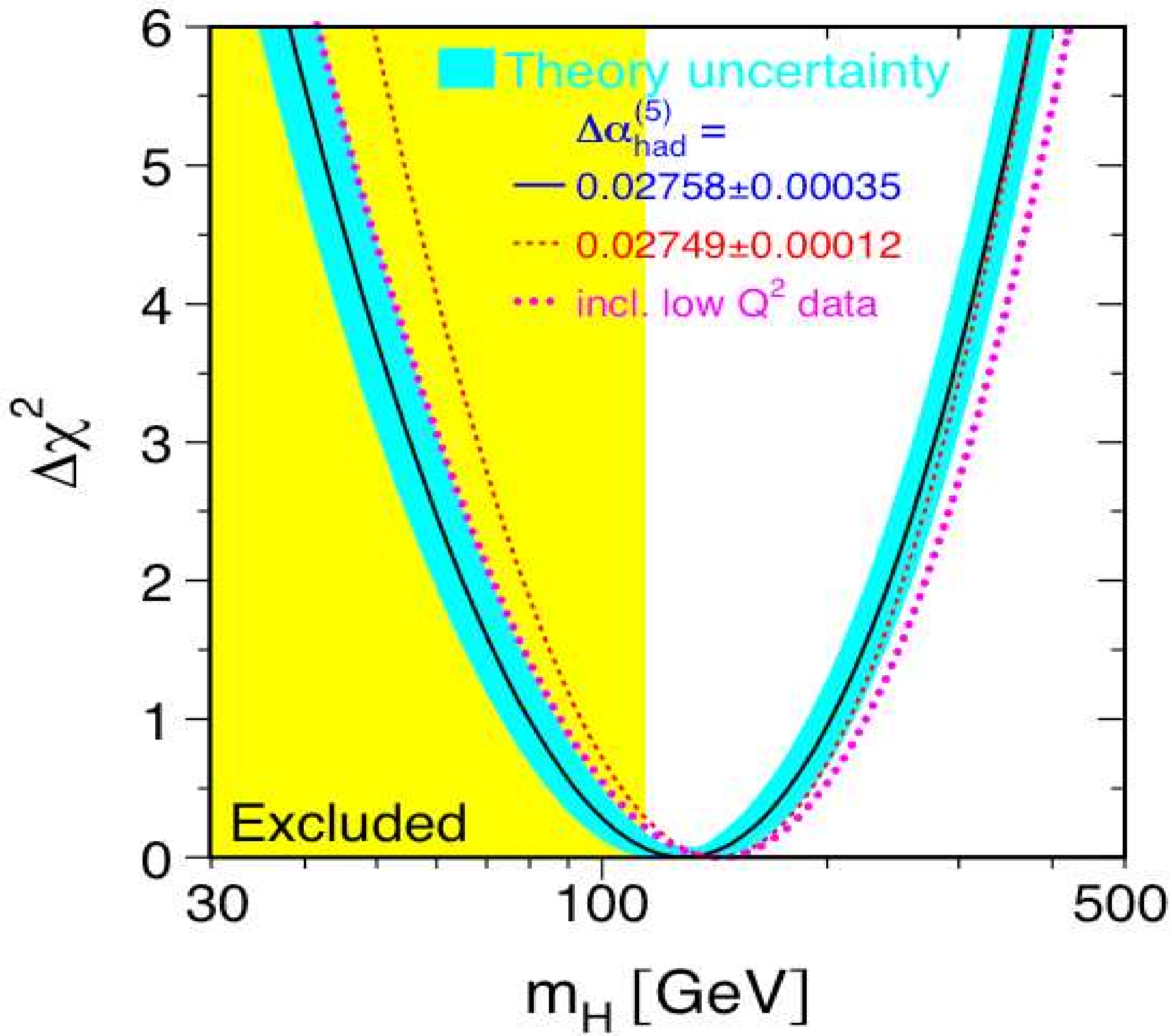
Indications for New Physics

- Typical processes mediated by force carrying Bosons



- Loop corrections are important
  - Known standard model particles for X do not explain data from Tevatron, LEP, SLC
  - Need something new- Higgs, Supersymmetry, Technicolor, other?
  - Data indicate that the masses of X are in the few hundred Gev range

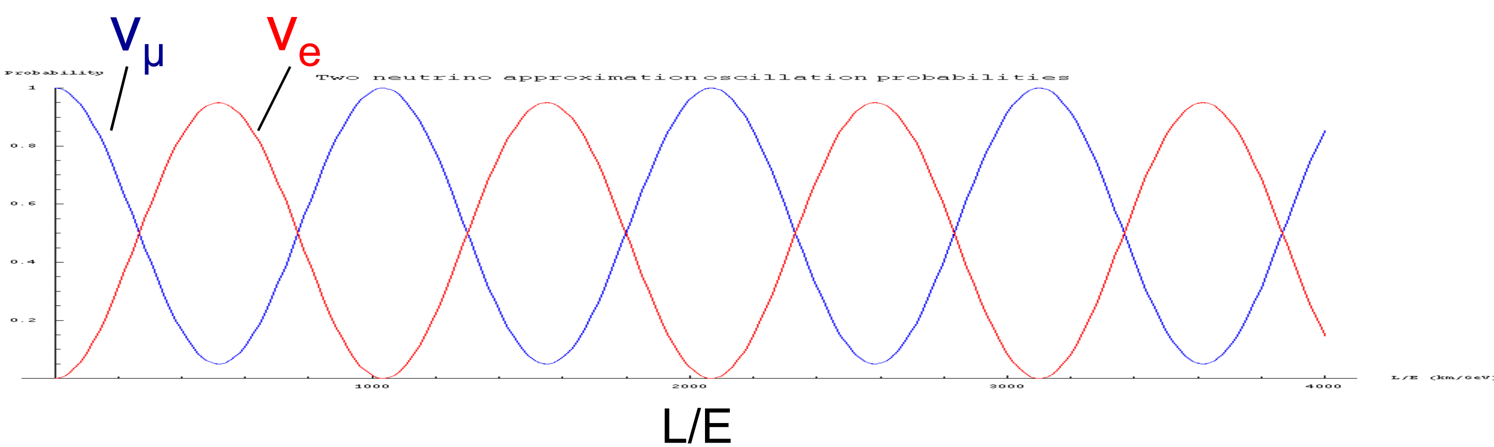
Constraints on the Higgs Mass



Neutrino Oscillations

As a beam of neutrinos with two mass eigenstates (Δm) propagate, the different mass eigenstates have slightly different wavelengths. Beats between the two cause oscillations between the neutrino types

$$P(\nu_\mu \dashrightarrow \nu_e) = \sin^2(2\theta)\sin^2 (1.27\Delta m^2 L / E)$$



Experimental observation of neutrino oscillations:

a. Mixing between different neutrino types

b. Neutrinos have mass

The Neutrino Mixing Matrix

- The Quarks mix with each other
  - 3x3 quark mixing matrix includes a phase δ that causes the CP violation observed in K and B decays
  - This CP violation is not large enaugh to explain the matter-antimatter asymmetry in our universe
- The neutrinos also have a 3x3 mixing matrix
  - The neutrino mixing matrix also has a CP violating phase δ'
  - This CP violation in the lepton sector may (or may not!!) explain the observed matter-antimatter asymetry in the universe (i.e. why are we here?)
- Envision a staged neutrino program
  - Measure the last unknown mixing angle $\sin^2(2\theta_{13})$
  - Dirac or Majorana neutrinos? (neutrinoless double β decay)
  - Normal or inverted neutrino mass hierarchy
  - Look for CP violation (long baseline experiments)

How do we get there?

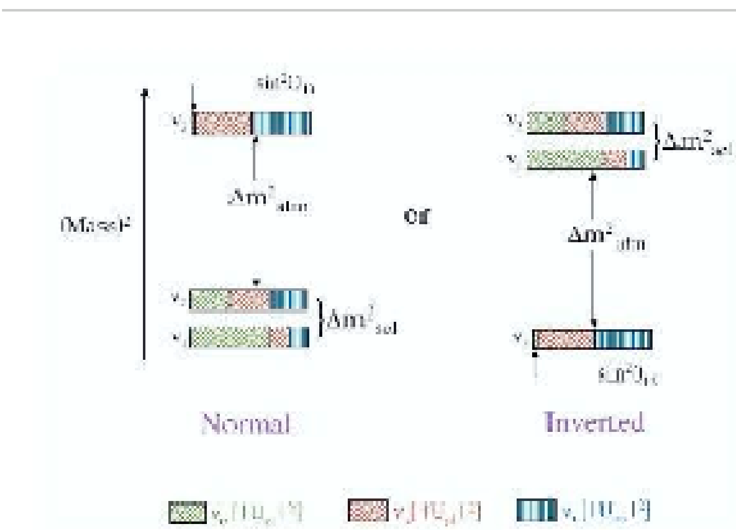
Staged approach in measuring $\sin^2 2\theta_{13}$, mass hierarhy, CP Violation

Three Neutrino Mixing Matrix:

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atomospheric}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{Cross-Mixing}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar}}$$

CP Violation Parameter



Neutrino mass ordering

Normal or Inverted Mass Hierarchy?

The Search for Dark Matter

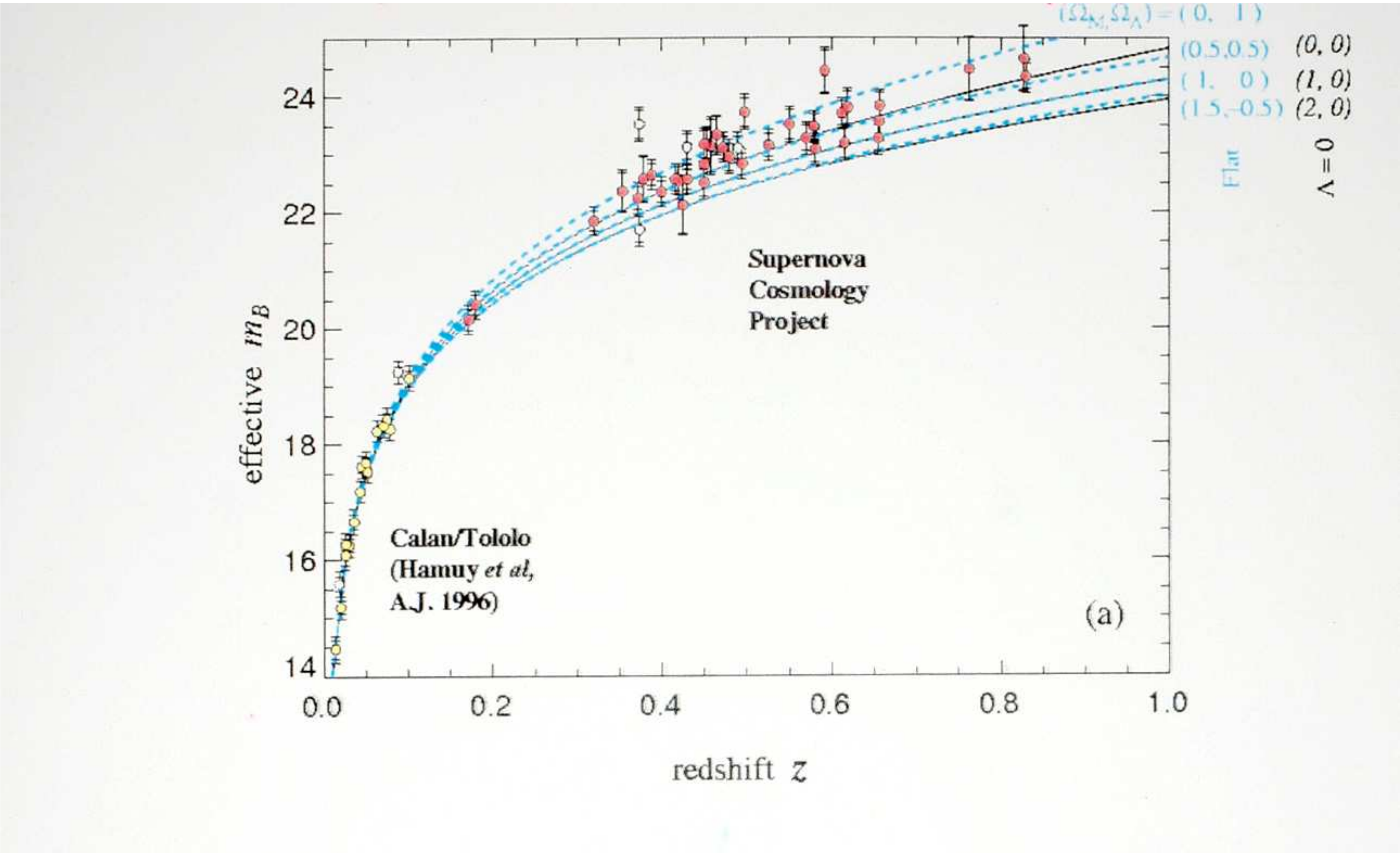
- Astronomers have known about Dark Matter for decades. It took a while for particle physicists to realize that this is also their problem…
- The LHC is likely to discover particles which will be candidates for DM
  - The lightest Supersymmetric particle??
  - LHC is likely to discover lots of other weird particles--which of these, if any, is DM?
- Need direct discovery of DM particles from space to show that properties are those of particle discovered by LHC

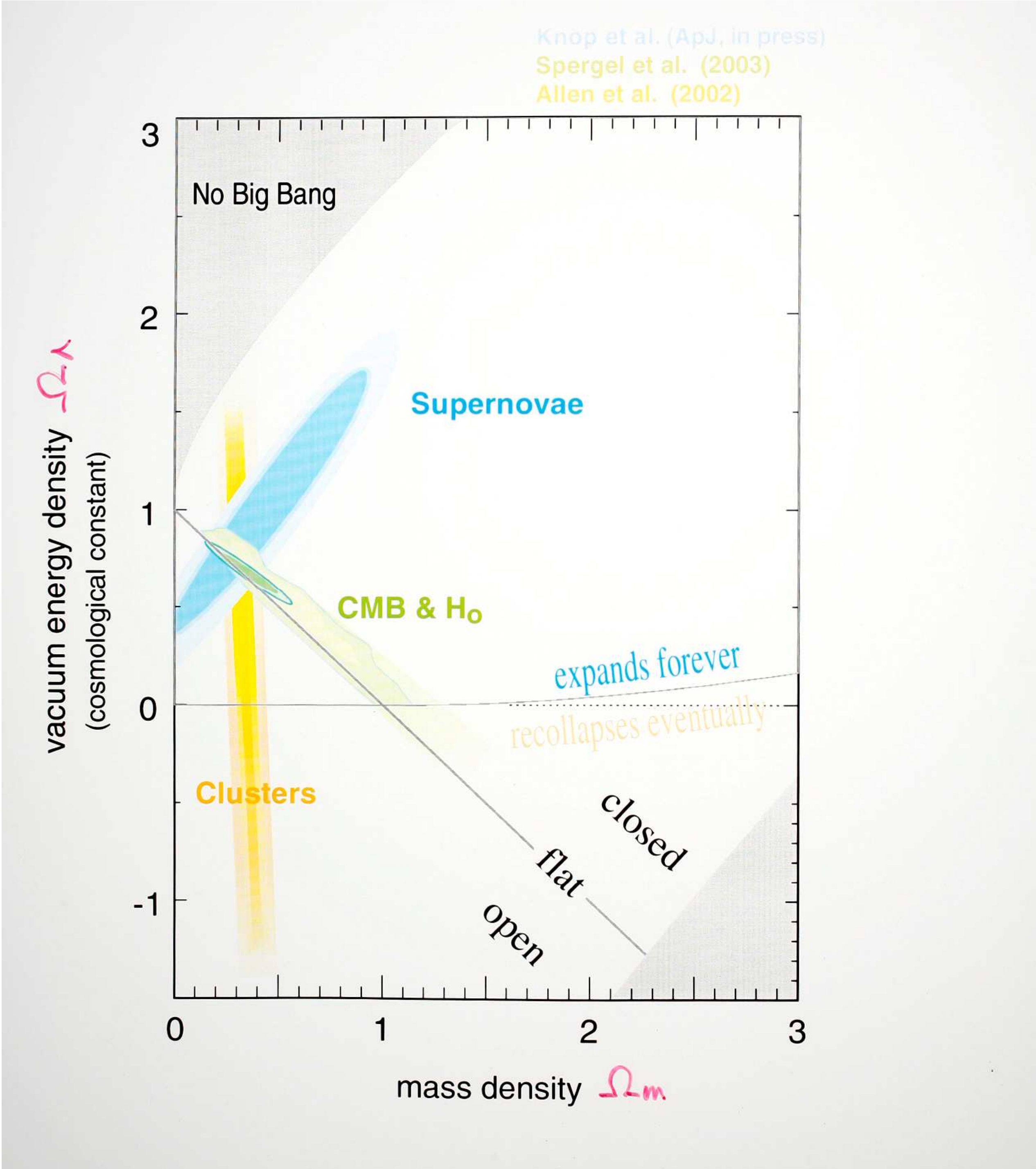
What is the Nature of Dark Energy

- Evidence for an accelerating expansion of our Universe introduced the need for something new, Dark Energy, different from Dark Matter or anything else we know of (repulsive Gravity,negative pressure,…)
- New Concordance model for the constituents of the Universe:
  - ~ 4 % Baryonic stuff
  - ~24 % Dark Matter
  - ~72 % Dark Energy
- The nature of Dark Energy is a central question in Particle Physics

Evidence for an accelerating Universe

S. Perlmutter etal (Berkeley)
A. Riess et al (Harvard)




Knop et al. (ApJ, in press)
Spergel et al. (2003)
Allen et al. (2002)
No Big Bang
Supernovae
CMB & H_o
expands forever
recollapses eventually
Clusters
closed
flat
open
vacuum energy density Ω_Λ
(cosmological constant)
mass density Ω_m
3
2
1
0
-1
0
1
2
3

3/19/05

A set of interrelated questions define the field

1. How do particles acquire mass? Does the Higgs boson exist, or are new laws of physics required?
2. What is the nature of new particles and new principles beyond the Standard Model?
3. What is the dark matter that makes up about one quarter of the contents of the universe?
4. What is the nature of the dark energy that makes up almost three quarters of the universe?
5. Do all the forces of nature become one? How does gravity fit in? Is there a quantum theory of gravity?
6. Why is the universe as we know it made of matter, with no antimatter present? What is the origin of this matter-antimatter asymmetry?
7. What are the masses and properties of neutrinos and what role did they play in the evolution of the universe? How are they connected to matter-antimatter asymmetry?
8. Is the building block of the stuff we are made of, the proton, unstable?
9. How did the universe form?

The Three Frontiers of Particle Physics

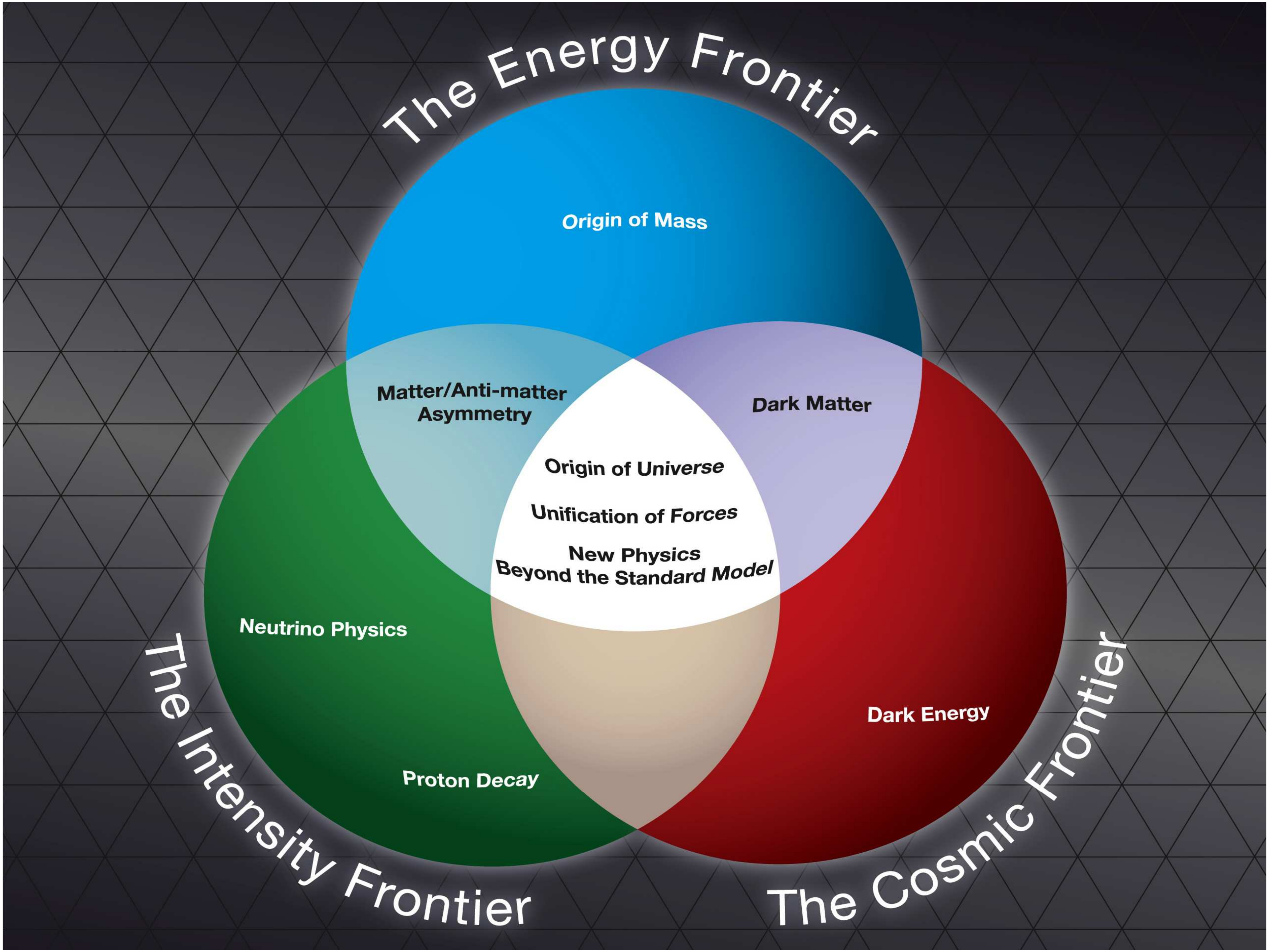
Addressing the central questions of the field requires a broad program of research using a variety of tools and techniques that we broadly classify into three interrelated frontiers:

- The Energy Frontier, using high-energy colliders to discover new particles and directly probe the properties of nature.

- The Intensity Frontier, using intense beams to uncover the elusive properties of neutrinos and observe rare processes that probe physics beyond the Standard Model.

- The Cosmic Frontier, revealing the natures of dark matter and dark energy and using high-energy particles from space to probe the architecture of the universe.

These three frontiers form an interlocking framework that addresses fundamental questions about the laws of nature and the cosmos.



The Energy Frontier
Origin of Mass
Matter/Anti-matter Asymmetry
Dark Matter
Origin of Universe
Unification of Forces
New Physics Beyond the Standard Model
Neutrino Physics
Proton Decay
Dark Energy
The Intensity Frontier
The Cosmic Frontier

The Changing face of US Particle Physics

- Particle physics in the United States is in transition. Two of the three high-energy physics colliders in the US have now permanently ceased operation. The third, Fermilab's Tevatron, will turn off in the next few years.
- The Energy Frontier, defined for decades by Fermilab's Tevatron, will move to Europe as CERN's Large Hadron Collider begins operations. American high-energy physicists have played a leadership role in developing and building the LHC program, and they constitute a significant fraction of the LHC collaborations—the largest group from any single nation. About half of all US particle physicists participate in LHC experiments.
- The Intensity Frontier will be Fermilab's future main emphasis, with a long baseline neutrino program to the DUSEL underground lab
- The Cosmic Frontier: non-accelerator experiments will play an increasingly important role in particle physics

The Energy Frontier

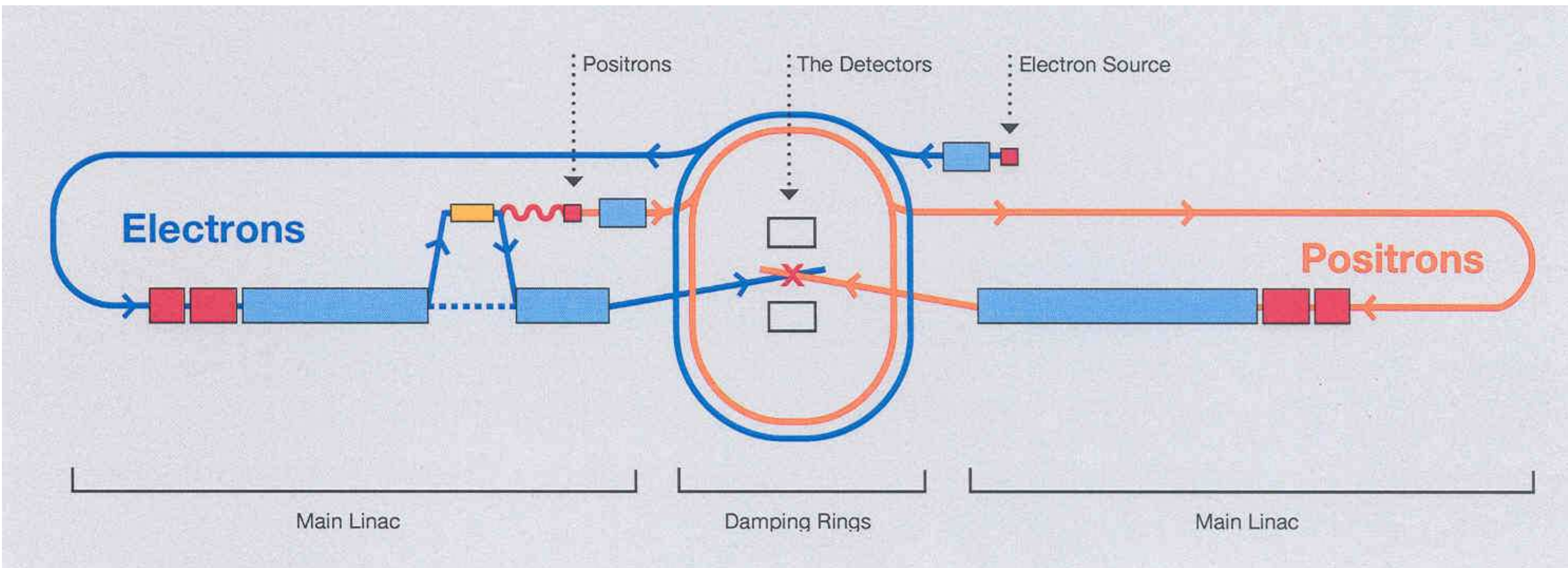
The Energy Frontier

- Accelerators and experiments at the Energy Frontier are expected to make major discoveries leading to an ultimate understanding of the theory of particles and their interactions. They will address key questions about the physical nature of the universe: the origin of particle masses, the existence of new symmetries of nature, extra dimensions of space, and the nature of dark matter
- The Tevatron Collider at Fermilab, until recently the highest-energy collider in the world, will cease operations in one or two more years.
- The Large Hadron Collider at CERN in Geneva, Switzerland will achieve the highest collision energies. The LHC is an international project with significant US investment and major US involvement: Americans constitute the largest group of LHC scientists from any single nation. Significant US participation in the full exploitation of the LHC has the highest priority in the US particle physics program.

The International Linear Collider (ILC)

250 Gev e^+ + 250 Gev e^- ---> 500 Gev in center of mass

Upgradeable to 1 Tev in c of m



Complementarity of Hadron and Lepton Colliders

- Hadron Colliders-- p on p or p^- on p
  - Protons are composites of quarks and gluons
    - Complicated, unknown initial states
    - Complex final states
    - Only a fraction(10%?) of the pp energy goes into the interesting quark-quark collision
  - Can make most anything, good for discovering unexpected new phenomena, high energy reach
- Lepton Colliders--e^+ on e^- or μ^+ on μ^-
  - Pointlike particles, well defined initial states
  - Relatively simple final states
  - Suited for detailed understanding of new physics

Interplay of Proton and Electron accelerators

Proton Accelerators	Electron Accelerators
AGS(30 Gev p) discovered bump J	SPEAR(3 Gev e+e-) interpretation as charm charmed particle spectroscopy
FNAL(400 Gev p) discovered bump Υ	CESR (10 Gev e+e-) interpretation as b quark particles with b quarks
CERN SppS(800 Gev pp) discovered W, Z	LEP, SLC (100 Gev e+e-) detailed precision electroweak
LHC (14 Tev pp) discovery of X…	ILC (0.5 - 1.0 Tev e+e-) detailed understanding of new physics

Lepton Colliders

- The international particle physics community has reached consensus that a full understanding of the physics of the Terascale will require a lepton collider as well as the LHC. The panel reiterates the importance of such a collider.
- In the next few years, results from the LHC will indicate the required energy for such a lepton collider.
- If the optimum initial energy proves to be at or below approximately 500 GeV, then the International Linear Collider is the most mature option with a construction start possible in the next decade.
  - The cost and scale of a lepton collider mean that it would be an international project, with the cost shared by many nations.
  - International negotiations will determine the siting; the host will be assured of scientific leadership at the energy frontier.
- A requirement for initial energy much higher than the ILC's 500 GeV will mean considering other collider technologies.
- Whatever the technology of a future lepton collider, and wherever it is located, the US should plan to play a major role.

The Intensity Frontier

The Intensity Frontier

- Measurements of the mass and other properties of neutrinos are fundamental to understanding physics beyond the Standard Model and have profound consequences for understanding the evolution of the universe.
- The US can build on the unique capabilities and infrastructure at Fermilab, together with the proposed DUSEL, the Deep Underground Science and Engineering Laboratory proposed for the Homestake Mine, to develop a world-leading program in neutrino science.
- Such a program will require a multi-megawatt proton source at Fermilab.

Vision for the Neutrino Program

- Goals of the program:
  - Measure Neutrino mixing matrix elements (θ_{13})
  - Neutrino masses, mass ordering (mass hierarchy)
  - Discover and measure CP violations in neutrino sector
- A vision for the long range US neutrino program:
  - Intense neutrino beam from Fermilab needs multi-megawatt proton source
  - Long baseline with large detector at DUSEL
  - May later need improved neutrino beam from a Neutrino factory using a muon storage ring
- Such an ambitious program needs to proceed in steps
  - NOvA with 700 kW source
  - Phase 1 detector in Homestake Mine with 700 kW source
  - Full size detector in Homestake Mine with 2 MW source
  - Beam from Neutrino Factory if needed later

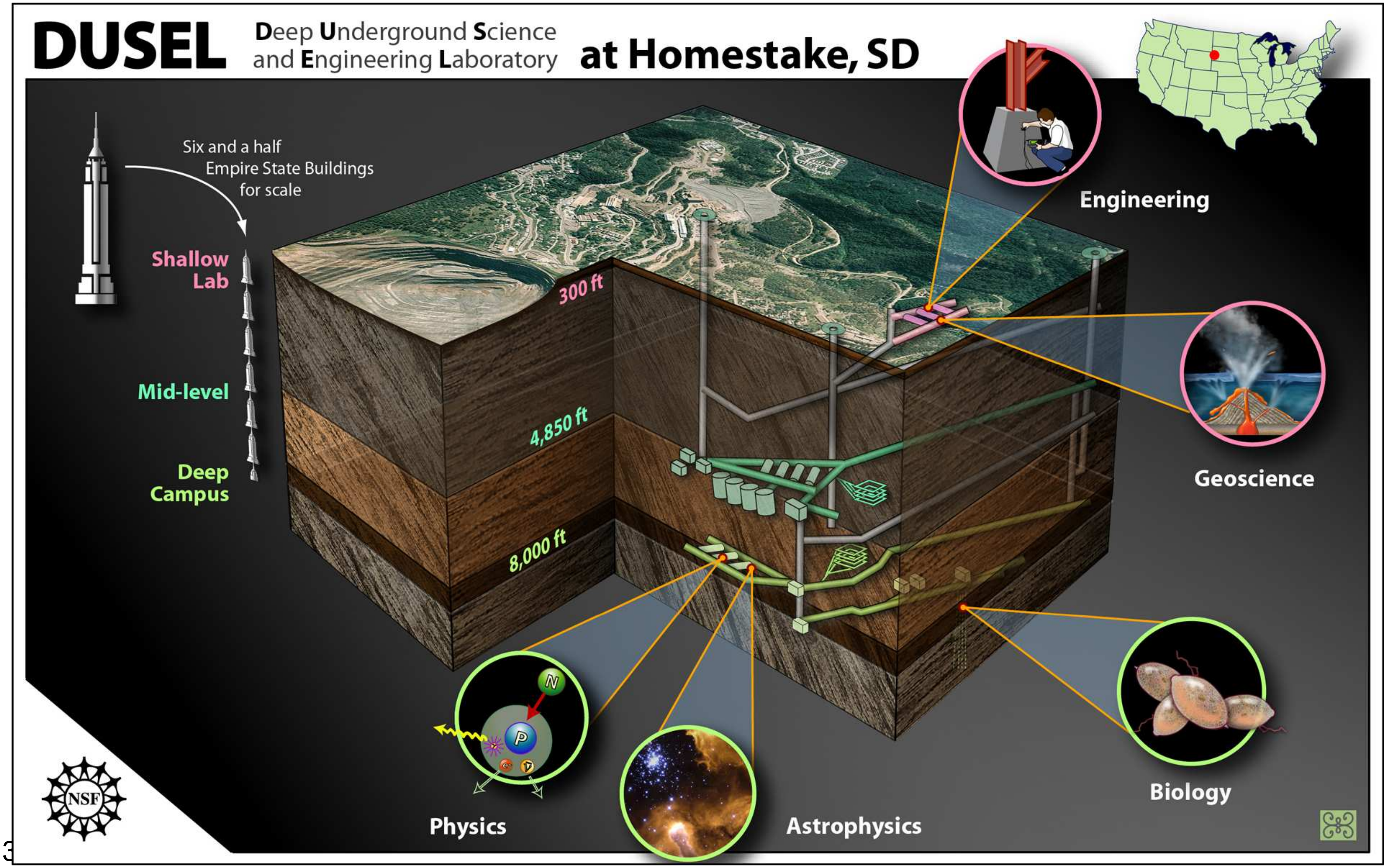
Precision Measurements : Quarks, Leptons, and Neutrinos

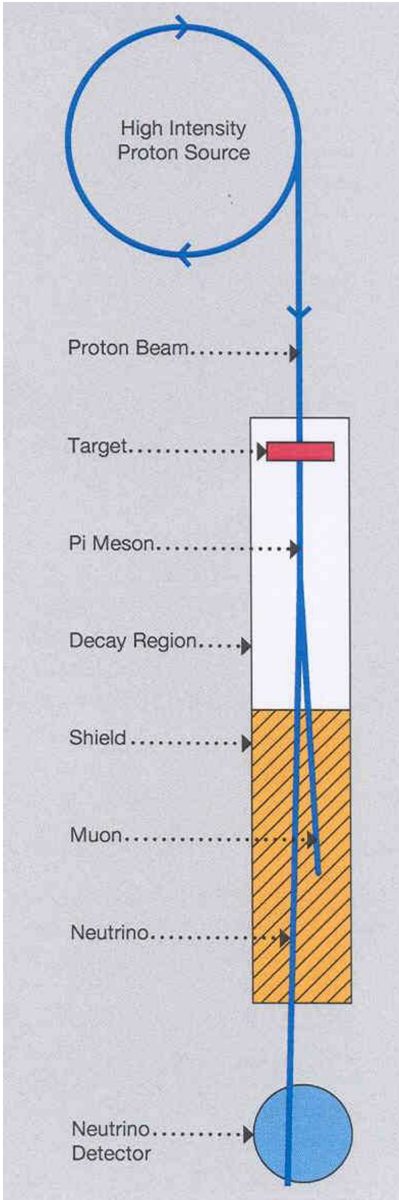
- Double Chooz and Daya Bay reactor neutrino expts should measure the last neutrino mixing angle, θ_{13}, which is needed to optimally design the future experiments at DUSEL.
- Non-accelerator experiments searching for neutrinoless double beta decay can distinguish between Dirac and Majorana neutrinos.
- The search for muon-to-electron conversion can now be done 4 orders of magnitude better than before, providing a powerful probe of new physics at high energies.
- The next generation B factories will probe the matter-antimatter asymmetry and study rare processes with at least an order of magnitude greater sensitivity than at BaBar and Belle.
- Rare K decay Experiments are sensitive to new physics at extremely high energy scales.

The DUSEL Facility

- The physics program of the Deep Underground Science and Engineering Laboratory is of central importance to particle physics. Experiments at DUSEL would address many high-priority issues in:
  - neutrino physics
  - search for proton decay
  - dark matter searches
  - neutrinoless double beta decay.
- The NSF should make this facility a reality as rapidly as possible.
- DOE and NSF should work together to realize the experimental particle physics program at DUSEL and define clearly the stewardship responsibilities.

DUSEL at Homestake





Conventional Neutrino Beams

P + target ---> π's + K's +…..

| |→ ν_e

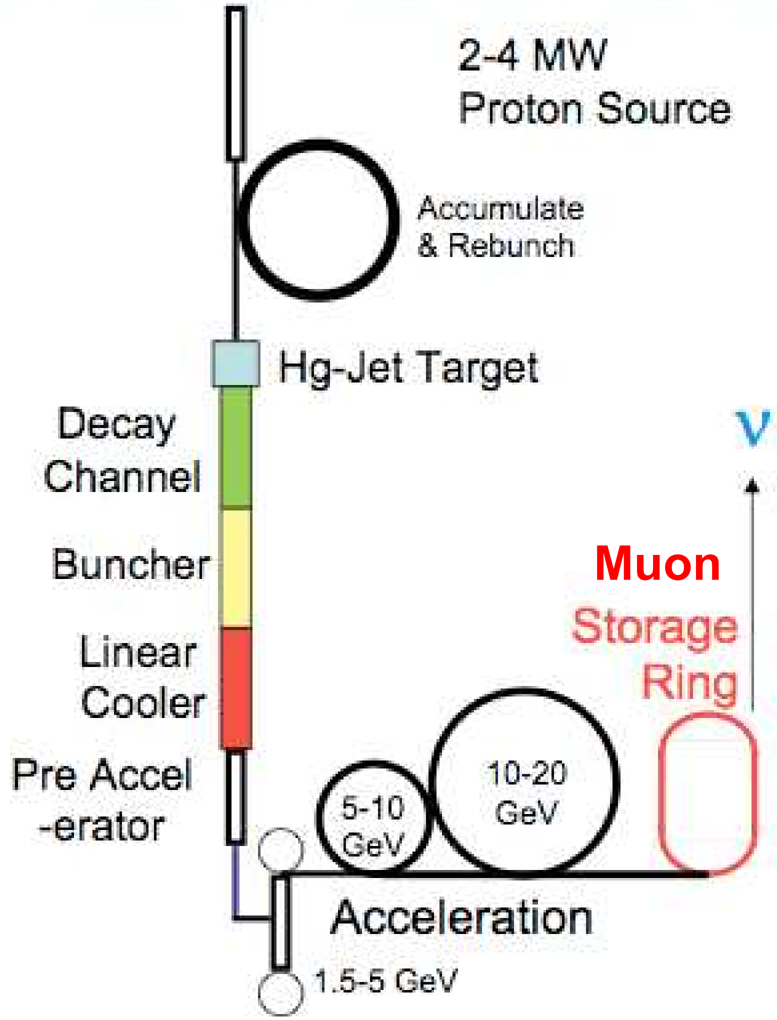
|→ ν_μ

Signal in ν_μ to ν_e oscillation expts is the appearance of a ν_e in a ν_μ beam

ν_e from K decays is often a limiting background

NEUTRINO FACTORY INGREDIENTS

- Proton Source
  - primary beam on production target
- Target, Capture, and Decay
  - create π; decay into μ
- Bunching & Phase Rotation
  - reduce ΔE of bunch
- Cooling
  - reduce transverse emittance
- Acceleration
  - 130 MeV $\rightarrow E_{NF}$
- Storage Ring
  - store for 500 turns; long straight section



US Design schematic: 20 GeV NF
(Phys. Rev. ST Accel. Beams 9, 011001 (2006))

The Cosmic Frontier

The Cosmic Frontier

- Although ninety five percent of the universe appears to consist of dark matter and dark energy, we know little about them.

- The quest to elucidate the nature of dark matter and dark energy is at the heart of particle physics—the study of the basic constituents of nature, their properties and interactions.

- The US is presently a leader in the exploration of the Cosmic Frontier. The field has identified compelling opportunities for dark matter search experiments, and for both ground-based and space-based dark energy investigations.

Dark Matter Search Experiments

- The LHC is likely to discover particles which will be candidates for DM
  - The lightest Supersymmetric particle??
  - LHC is likely to discover lots of other weird particles--which of these, if any, is DM?
- Need direct discovery of DM particles from space to show that properties are those of particle discovered by LHC
  - First generation Expts ~ 10 kg detectors, such as CDMS,XENON10, ADMX, WARP, ZEPPLIN, etc
  - Second generation Expts ~ 100 kg detectors such as SCDMS, XENON100,LUX, DEAP/CLEAN, etc
  - Third Generation Expts ~kiloton detectors: choice of technologies yet to be made

Experiments to Study the nature of Dark Energy

- The cause of the accelerated expansion of the universe is a mystery. It could signal the existence of a new form of energy, dark energy, or a breakdown of Einstein general relativity.

- For the near term, ground based experiments such as the Dark Energy Survey (DES) and BOSS, will advance our understanding considerably.

- For the longer term, the space-based Joint Dark Energy Mission and the ground-based LargeSynoptic Survey Telescope (LSST) and BigBOSS spectroscopic survey offer major complementary advances in probing the nature of dark energy.


SNAP
Supernova / Acceleration Probe
Studying the Dark Energy of the Universe